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Enhanced Virtual Synchronous Generator Control with Fuzzy Logic Controller for Parallel Inverters in Microgrids

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Abstract

Objective: To reduce the power oscillations and also to provide accurate active power and reactive power sharing.
Methods: In this paper enhanced Virtual Synchronous Generator (VSG) control strategy along with Fuzzy Logic Controller (FLC) is employed for parallel inverters in microgrids. It deals with design of the system and simulation results shows the improvement obtained through it.
Findings: By using enhanced VSG control, the oscillation damping and proper transient active power sharing are achieved by adjusting the virtual stator reactance and also accurate reactive power sharing is achieved based on inversed voltage droop control. Furthermore, FLC is used as suitable controllable mechanism (which was PI in basic VSG) for controlling the parallel inverters in microgrids with which power oscillations are further damped and accurate active and reactive power sharing are achieved. The simulation results prove that the proposed method is better than the basic VSG for parallel inverters in microgrids.
Application: This scheme is used for control of inverters in distributed source environments. This is essential for the operation of large AC systems, where distances between inverters make communication impractical. Use of multilevel inverters or an adaptive neuro-fuzzy inference system (ANFIS) can be considered as improvement for this paper.

Keywords: Distributed Power Generation, Droop Control, Fuzzy logic controller, Microgrids; Reactive Power Control, Virtual Synchronous Generator Control1.

1. Introduction

Nowadays, more and more distributed generation and renewable energy sources, e.g. wind, solar and tidal power, are connected to the public grid via power inverters. They often form microgrids before being connected to the public grid[1]. Due to the availability of high current power electronic devices, it is inevitable that several inverters are needed to be connected in parallel for high-power and/or low-cost applications. Inverters are also often connected in parallel to provide system redundancy and high reliability, which is important for critical customers. A natural problem for parallel-connected inverters is that how the load is shared among them. The control strategies of microgrids are preferred to be in a communication-less way because of its decentralized feature. Instead of the fact, that in a hybrid microgrid control structure, communication is required for the secondary and tertiary control, it is still prescribed to understand the fundamental functions of a microgrid in the primary control level without communication[2,3]. A key technique is to use the droop control, which is widely used in conventional power generation systems. The advantage is that no external communication mechanism is needed among the inverters. By drooping the frequency against the active power (P–ω droop) and the output voltage against reactive power (Q–V droop), load sharing between DGs

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can be performed in an autonomic way, which is like the power sharing between parallel Synchronous Generators (SGs)[4,5]. In a few references[6–8], it is suggested that P–V and Q–ω droop controls are more appropriate for Low Voltage (LV) microgrid by including resistive line impedance feature. At the same time, the P–ω and Q–V droop controls are still valid in LV microgrid by including inductive virtual impedance[9].

The droop control provides barely any inertia support to the microgrid, therefore a droop control-based microgrid is more often inertia less and sensitive to fault. To provide inertia support for the system, control techniques to imitate virtual inertia are proposed in recent literatures, like Virtual Synchronous Generator (VSG)[10–13], virtual synchronous machine and synchro-converter. Although they differ in name and have different control schemes but their principles are similar in the aspect that all of them imitate the transient characteristics of SG by following its fundamental swing equation. For simplicity, all of those methods are called VSG control in this paper. To share the load in parallel operation, droop characteristics are also emulated in some VSG control strategies. In this case, VSG control acquires the benefits of droop control, and outperforms the latter in terms of transient frequency stability owing to its lower df/dt rate. Thus, VSG control can be considered as an enhanced method for the communication-less control strategy of a microgrid.

When basic VSG control is employed in microgrids, a few issues have been seen, like oscillation in active power during a disturbance, improper transient active power sharing during load transition and errors in reactive power sharing.

Active power oscillation during a disturbance is introduced by the notable component of the swing equation, hence it is an inherent feature for a genuine SG as well as a VSG. It is not a major issue for SGs since they normally have considerable over-load capacities, but the over-load capabilities of inverter-interfaced DGs are not sufficient to ride though a large oscillation. However, this oscillation can be damped by properly expanding the damping proportion or utilizing alternating moment of inertia. Utilizing smaller inertia may lead to reduced oscillation. So, it is not encouraged as providing a large amount of virtual inertia is an advantage of VSG from other control techniques.

In this paper, oscillation damping is achieved based on varying the virtual stator reactance. Because of the oscillatory feature of VSG, improper transient active power sharing during load transition may also cause oscillation, which is avoidable if the swing equation and output impedance are designed properly.

The inaccurate reactive power sharing is a well-known problem in both conventional Q–V droop control, and P–V droop control. In Q–V or P–V droop controls, output voltage is regulated according to reactive/active power sharing, but the output voltage of each DG is not equal due to unequal line voltage drop. A comprehensive solution is to eliminate the mismatch of DG output impedance. But, this method cannot guarantee accurate reactive power sharing if active power is not shared according to the power rating ratio. However, as accurate reactive power sharing is a basic function of a microgrid, it is always preferred to solve this problem in a communication-less manner.

In this paper, a communication-less approach is presented based on inversed voltage droop control (V–Q droop control) and common ac bus voltage estimation. By applying the proposed method, reactive power sharing is immune to line impedance mismatch and active power sharing change. However, in these works, measured bus voltage is used directly, while, in microgrid applications, it may not be feasible if DGs are not installed in the proximity of the AC bus. In this paper, bus voltage is estimated based on the available local measurement, thus there should be no installation difficulty in the field applications.

2. Basic VSG Control Scheme

Figure 1, demonstrates the structure of a DG utilizing the basic VSG control. The primary source of the DG could be photovoltaic panels, fuel cells, a gas engine or other distributed energy resources (DERs). The energy storage is designed for emulating the kinetic energy stored in rotating mass of a SG, in request to supply or retain deficient/surplus power generated by the primary source in transient state[13]. As this paper concentrates on the control plan of the inverter, the outline and control of the primary source and energy storage are beyond the scope of this paper.

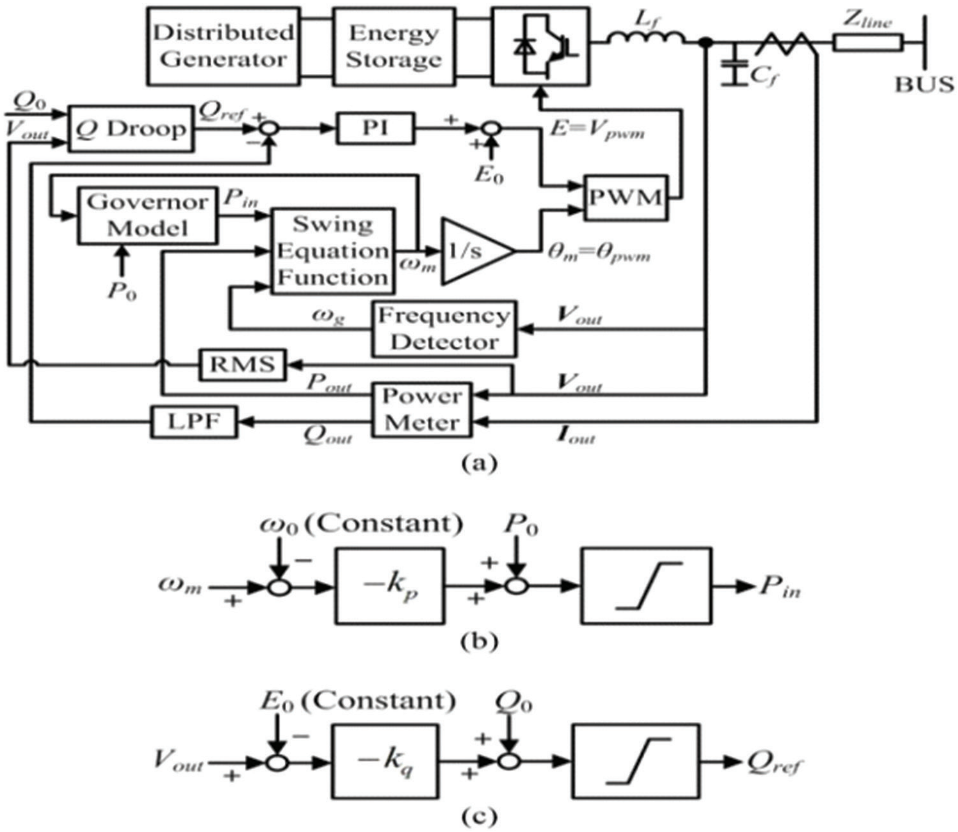


Figure 1. Block diagram of (a) the basic VSG control, (b) the "Governor Model" block and (c) the "Q Droop" block.

In the block "Swing Equation Function" in Figure 1(a), $\omega_m \omega_m$ is tackled from the swing equation (1) by an iterative technique.

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dx} + D(\omega_m - \omega_g) \quad (1)$$

The block "Governor Model" in Figure 1(a) is a ω–P droop controller as appeared in Figure 1(b). In some past studies[12] a first order lag unit is utilized to imitate the mechanical delay in the governor of a real SG. However, in this paper, this delay is removed, because it reduces the dynamic performance of DG.

The block "Q Droop" in Figure 1(a), is a V–Q droop controller as shown in Figure 1(c), which differs from the routine Q–V droop controller in the reversed input and output. It is essential that inner current or voltage loop is not implemented in this control method, in order to make the filter inductor L_f contribute to the output impedance and is considered as stator inductance of the VSG. This stator inductance brings out more inductive output impedance, which is particularly important for active and reactive power decoupling in a low voltage microgrid in which line resistance is dominant. However, output voltage is still controlled indirectly by the V–Q droop controller and the PI controller of reactive power. In order to reduce the impact from ripples in measured output power, a 20Hz first order low-pass filter is connected for Q_{out} as shown in Figure 1(a). As the output current is measured after the LC channel organize, the reactive power expended by the LC filter, the reactive power consumed by the LC filter is excluded in Q_{out}. So, no particular inertial process is required for the reactive power PI controller.

In a microgrid, in order to share the active and reactive power according to the ratings of DGs without communication, $k_p^* = {(k_p\omega_o)}/{S_{base}}$, $k_q^* = {(k_q E_o)}/{S_{base}}$, $P_o^* = {P_o}/{S_{base}}$ and $Q_o^* = {Q_o}/{S_{base}}$ should be designed similarly for every DG in default[2]. In this paper, to simplify the explication for the instance of various power ratings, per unit values are computed based on respective power ratings of DGs.

Figure 2 shows the structure of a microgrid in islanded mode which consists of two DGs. The DGs are connected to a common AC bus via a distribution line, to supply the loads in the microgrid. In the present work, this microgrid using VSG control is studied.

3. Proposed Enhanced VSG Control Scheme with FLC

The proposed enhanced VSG control strategy is shown in Figure 3. Compared to the basic VSG control, three noteworthy changes are made, i.e., the stator reactance adjuster and the bus voltage estimator, as shown in Figures 3(b) and 3(c), respectively and a fuzzy logic controller(FLC) instead of PI controller. The function of stator reactance adjuster is to change the output reactance of the DG freely. It is working as a virtual impedance controller. The virtual stator inductor is realized by multiplying output current by the virtual stator inductor in stationary case. It will be more precise if inductor current through L_f is used.

However, this increases the number of current sensors, which are unnecessary. As the current flowing into C_f at fundamental frequency is not as much as few percent of the inductor current, utilizing output current rather than inductor current does not influence the execution of the control scheme. Tuning of virtual stator inductor L_{ls} is recommended to set aggregate output reactance X_i^* for both DGs in same per unit value. This approach increases active power damping ratio and shares transient load without oscillation.

$$X_i^{2} = \frac{S_{base\,i}\,\omega_{m\,i}\left(L_{ls\,i} + L_f + L_{line\,i}\right)}{E_0^2} 0.7\ p.u \quad (2)$$

The L_{fi} and $Z_{line\,i}\left(R_{line\,i} + jL_{line\,i}\right)$ are considered as known parameters in this paper. As the size of microgrid is small, the line distance is easy to be measured. Even if it is not the case, several online measurement or intelligent tuning methods for Z_{linei} are available.

With the proposed design of stator reactance adjustment, oscillation in a VSG-control-based microgrid should be almost eliminated during loading transition in islanded mode. Especially, transition from grid-connected mode to islanded mode can also be considered as a loading$Q^*_{out1} - Q^*_{out2} = -k^*_q\left(\Delta\hat{V}^*_1 - \Delta\hat{V}^*_2\right)$on during an islanding event should also be eliminated with the proposed control strategy. As for other disturbances in islanded mode, e.g., change of active power set value of DG(s), connection/disconnection of DG(s), etc., oscillation cannot be eliminated, but can still be damped by the increased total output reactance.

The principle of bus voltage estimator in Figure 3(c) is simple to that of stator reactance adjuster in Figure 3(b). By calculating the line voltage drop in stationary case using measured output current and line impedance data, the bus voltage can be estimated from the difference of output voltage and calculated line voltage drop. Since the RMS value of estimated bus voltage Vbus for each DG should be approximately equal, accurate reactive power sharing can be obtained by using estimated bus voltages as the input references of "Q Droop" instead of respective output voltages of DGs.

However, if there is an estimation error in $\hat{V}_{bus}$, it will cause a reactive power sharing error. Assuming $\hat{V}^*_{bus1} = V^*_{bus} + \Delta\hat{V}^*_1$ and $\hat{V}^*_{bus2} = V^*_{bus} + \Delta\hat{V}^*_2$.

$$Q^*_{out1} - Q^*_{out2} = -k^*_q\left(\Delta\hat{V}^*_1 - \Delta\hat{V}^*_2\right) \quad (3)$$

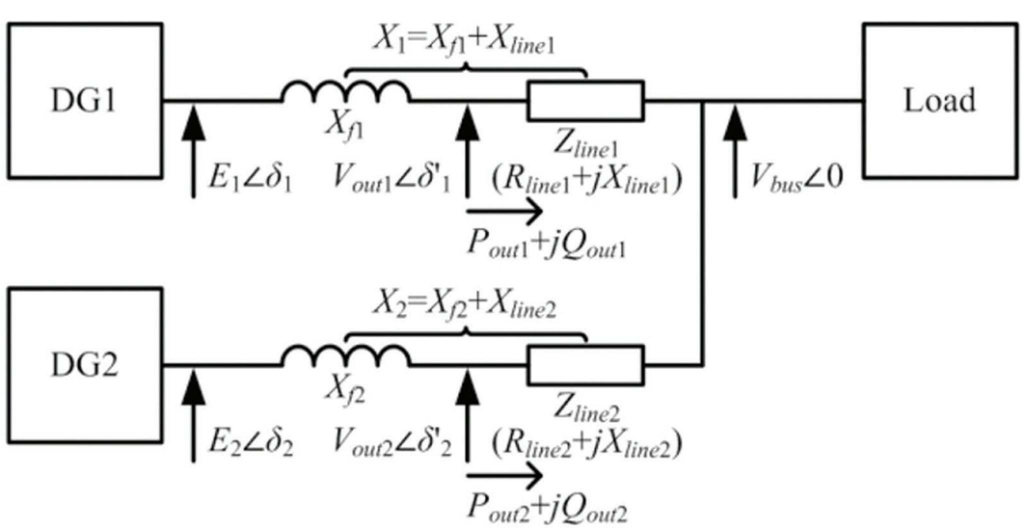


Figure 2. Structure of a microgrid in islanded mode.

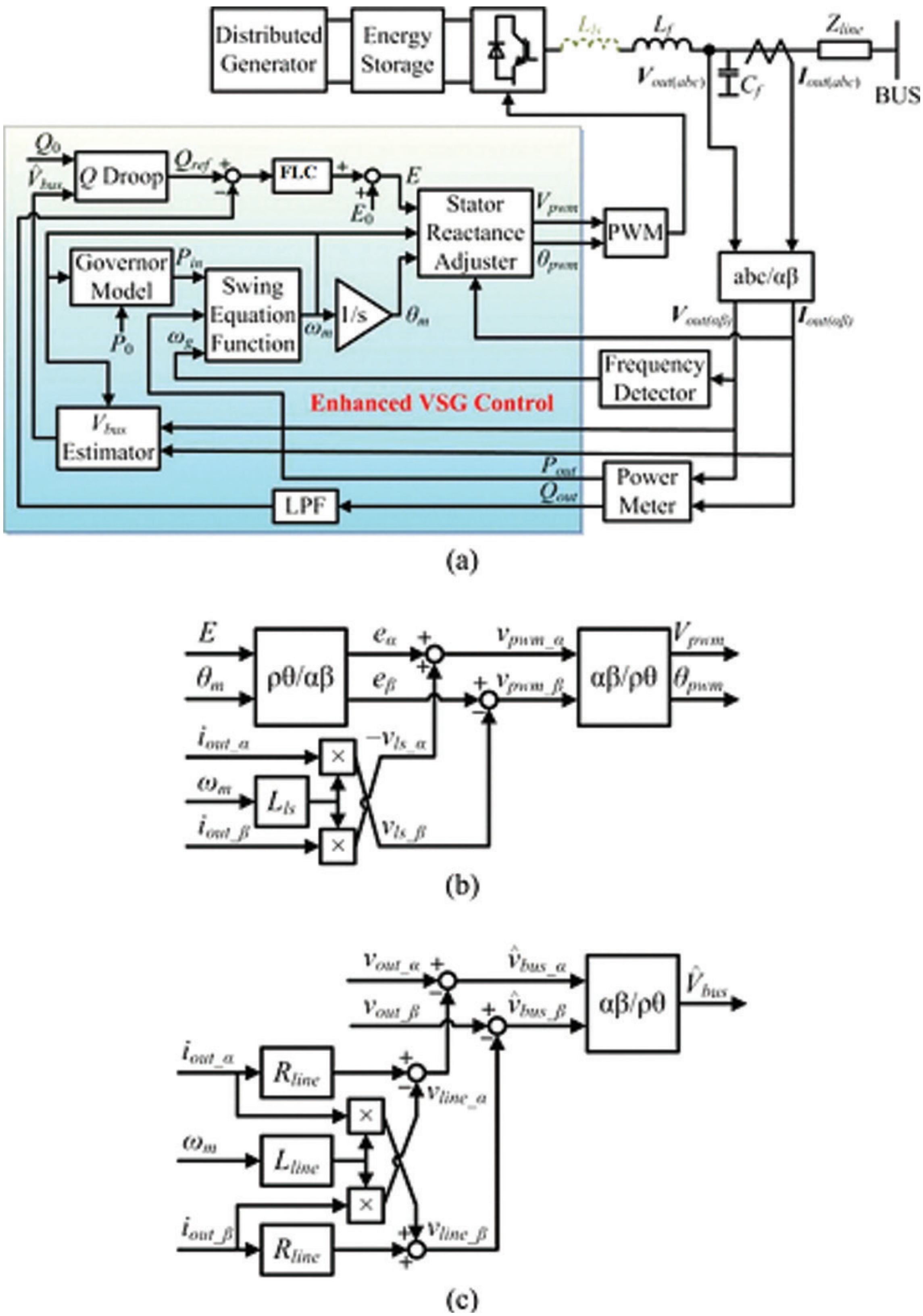


Figure 3. Block diagram of (a) the proposed enhanced VSG control, (b) the "Stator Reactance Adjuster" block and (c) the "VbusEstimator" block.

That is to state, that the reactive power sharing error occurred due to estimation errors is determined by the V–Q droop gain $k_{\dot{q}}$. The design of $k_{\dot{q}}$ is an exchange between voltage deviation and reactive power control accuracy.

4. Fuzzy Logic

Fuzzy rationale is a type of numerous esteemed rationales in which reality estimations of variables might be any genuine number somewhere around 0 and 1. Fuzzy rationale has been stretched out to handle the idea of halfway truth, where reality quality may extend between totally genuine and totally false. Besides, when etymological variables are utilized, these degrees might be overseen by particular capacities.

Normally fuzzy rationale control system is made from four noteworthy components exhibited on Figure fuzzification interface, fuzzy induction motor, fluffy principle grid and defuzzification interface.

The fuzzy rationale investigation and control strategies appeared in Figure 4 can be depicted as:

1. Receiving one or expansive number of estimations or other appraisal of conditions existing in some system that will be dissected or controlled.
2. Processing all got inputs as indicated by human based, fuzzy "assuming then" standards, which can be communicated in basic dialect words, and consolidated with conventional non-fuzzy preparing.
3. Averaging and weighting the outcomes from all the individual principles into one single output choice or sign which chooses what to do or advises a controlled system what to do. The outcome output sign is an exact defuzzified esteem. First of all, the different level of output (high speed, low speed etc.) of the platform is defined by specifying the membership functions for the fuzzy sets.

5. Simulation Results

A microgrid shown in Figure 5, is examined. As it is shown in Figure 5, impedances of output filters and lines of each DG vary in per unit values. The sequence of simulation is appeared in Table 1. Occasions of islanding from grid, loading transition, and intentional active power sharing change are simulated at 21 s, 24 s, and 27 s, respectively. The simulation results are shown in Figure 6.

As it is illustrated in Figure 6(a), when the microgrid is islanded at 21 s, and when load 2 is connected at 24 s, oscillation can be seen in active power when the basic VSG control is applied for both DGs.

This oscillation is nearly eliminated by applying the proposed enhanced VSG control shown in Figure 6(b). As the disturbance at 27 s is brought on by change of active power set estimation of DG1, which is most certainly not a loading transition, active power oscillation can't be eliminated with for this situation. However, the proposed upgraded VSG control increases the damping proportion. Therefore, the overshoots in Figure 6(b,) are smaller than that in Figure 6(a). Take note of that the rate of change of frequency remains same in all cases, which states that the proposed upgraded VSG control has no impact on the inertia support feature of VSG control.

In the case of basic VSG control, reactive power is not shared properly in islanded mode, and is not controlled at set value in grid-connected mode, because of the voltage drop through the line impedance, as shown in Figure 6(a). Also, reactive power control is not autonomous from active power control, as a change of set value of active power at 27 s will also causes a change of reactive power

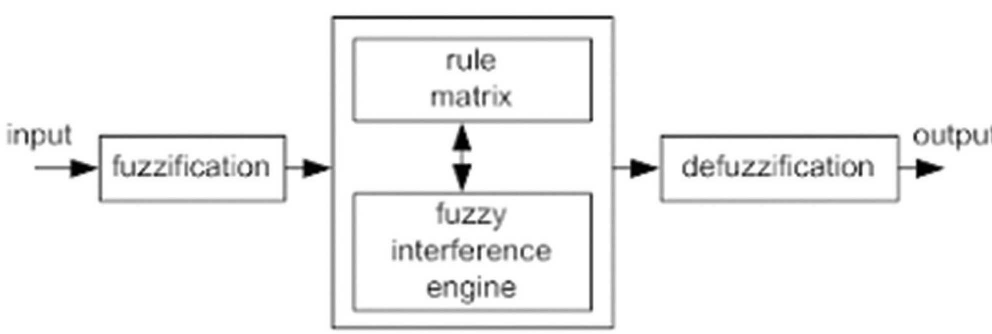


Figure 4. Block diagram of fuzzy logic controller.

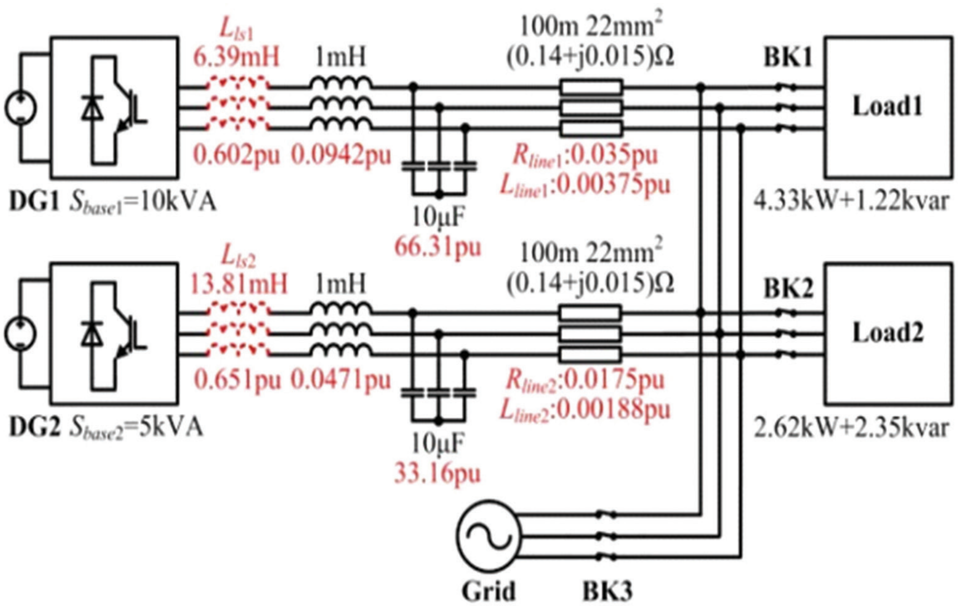
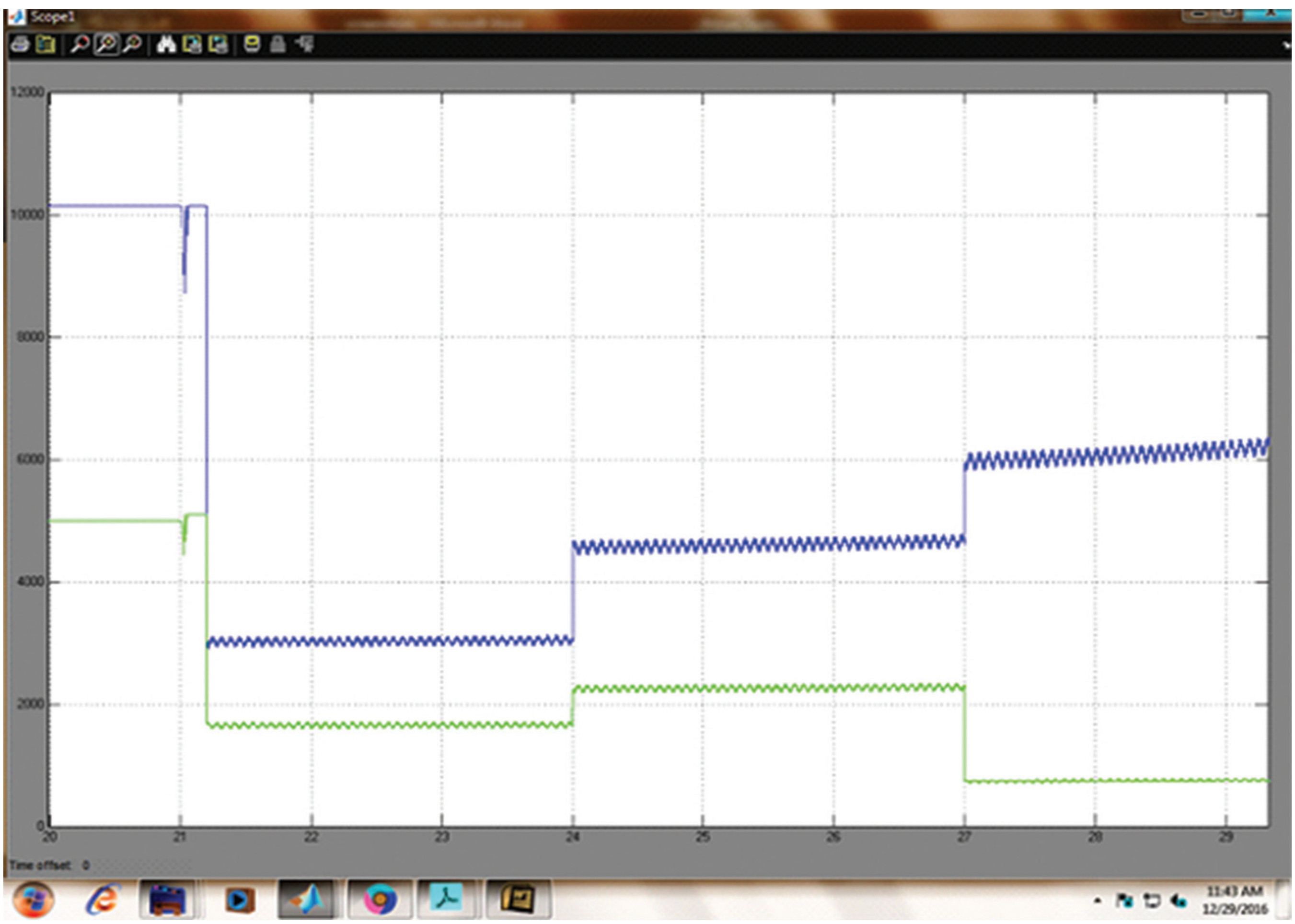
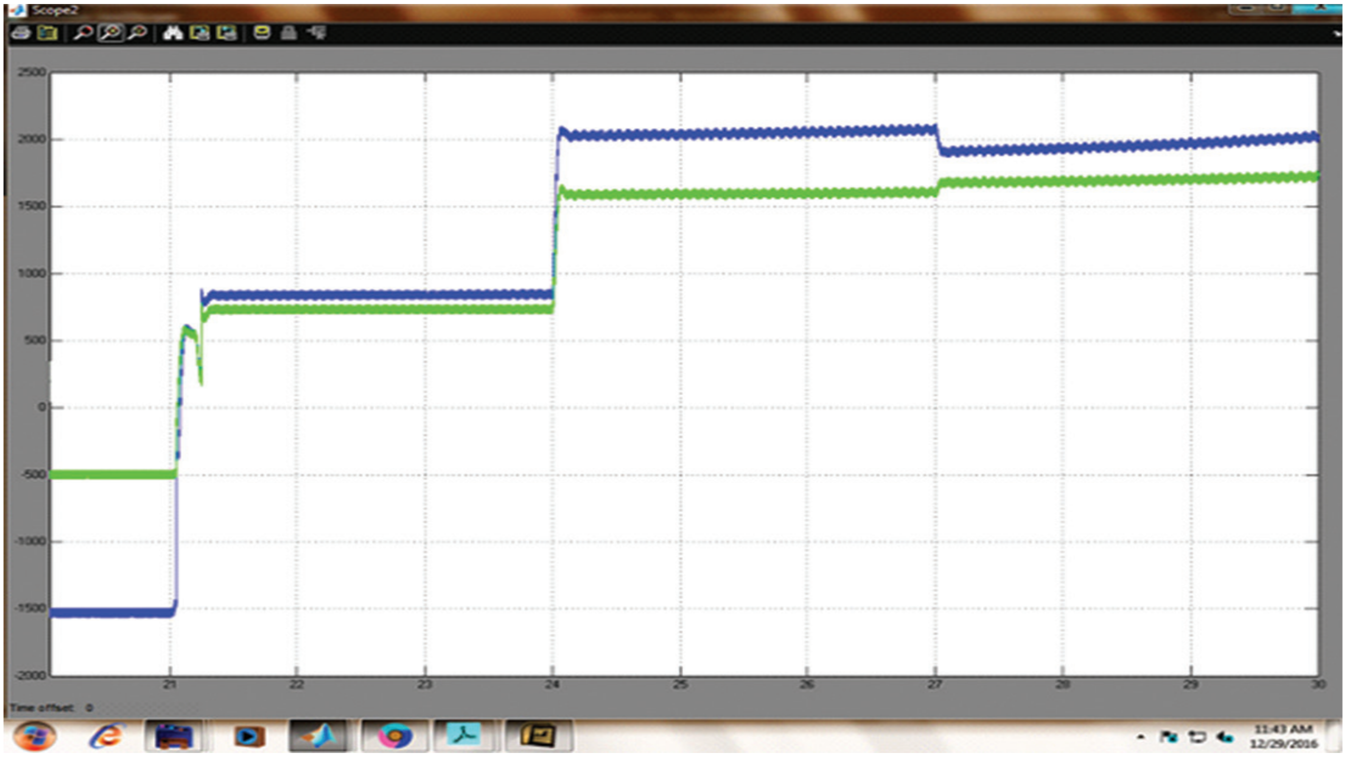


Figure 5. Simulation circuit.



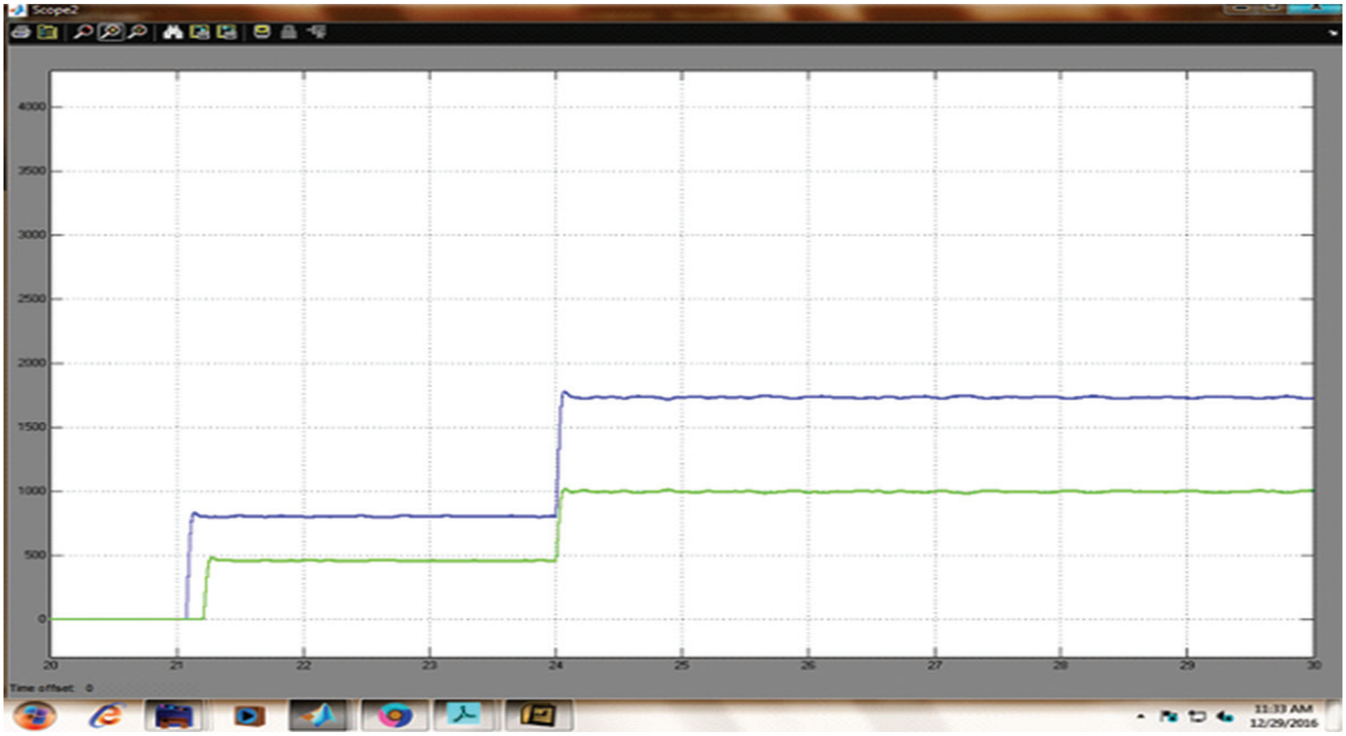
Active and reactive powers of load1



Active and reactive powers of load2

Figure 6 (**a**). Simulation results of active power and reactive power, when both DGs are controlled by basic VSG control.

Active and reactive powers of load1



Active and reactive powers of load2

Figure 6(b). Simulation results of active power and reactive power, when both DGs are controlled by enhanced VSG control with Fuzzy logic controller.

Table 1. Simulation sequence

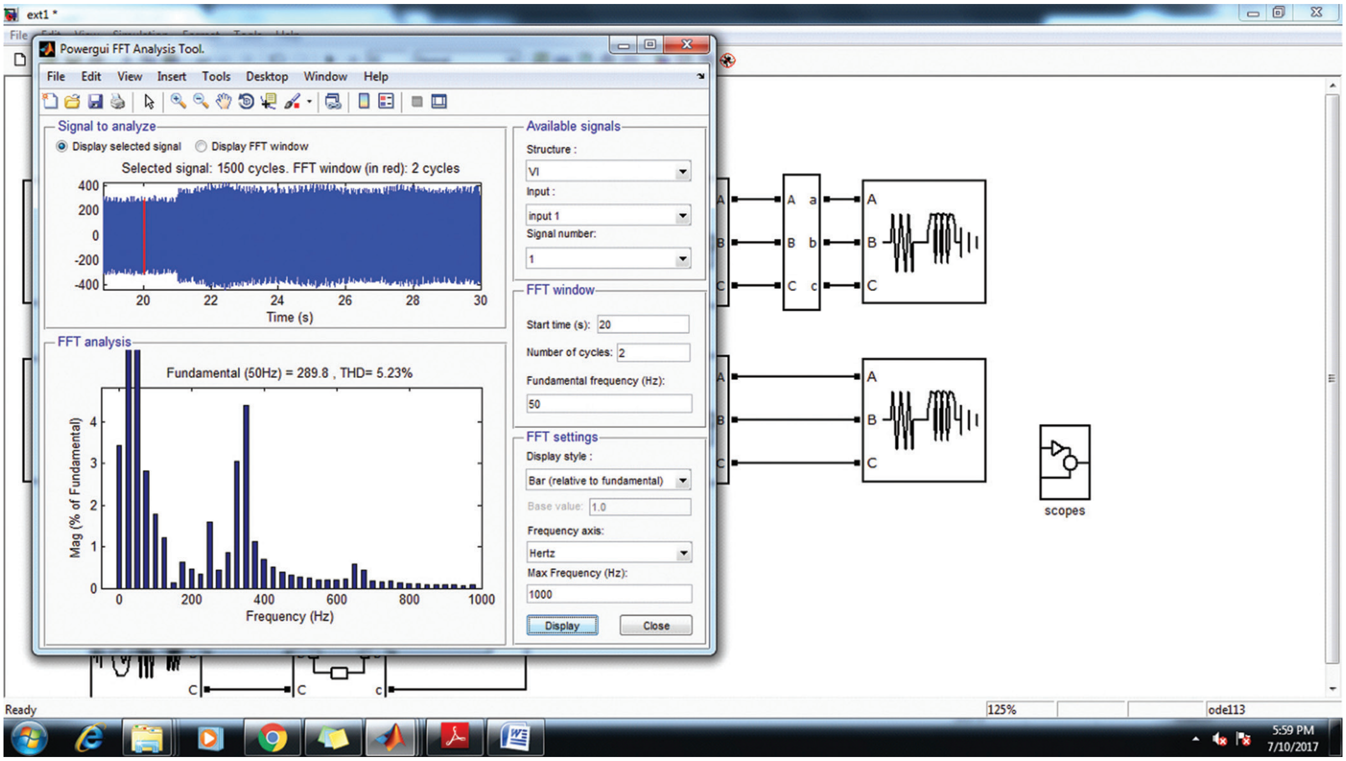
Time	Grid	P^*_{01}	P^*_{02}	Load
t < 21 s	connected	1 pu	1 pu	Load 1
21 s ≤ t ≤ 24 s	Disconnected	-	-	-
24 s ≤ t ≤ 27 s	-	-	-	Load 1+2
27 s ≤ t ≤ 30 s	-	-	0.6 pu	-

sharing. These issues are solved in the enhanced VSG control, as it is shown in Figure 6(b). It is also noted that the steady-state deviations of DG voltage and bus voltage become smaller when the enhanced VSG control is connected.

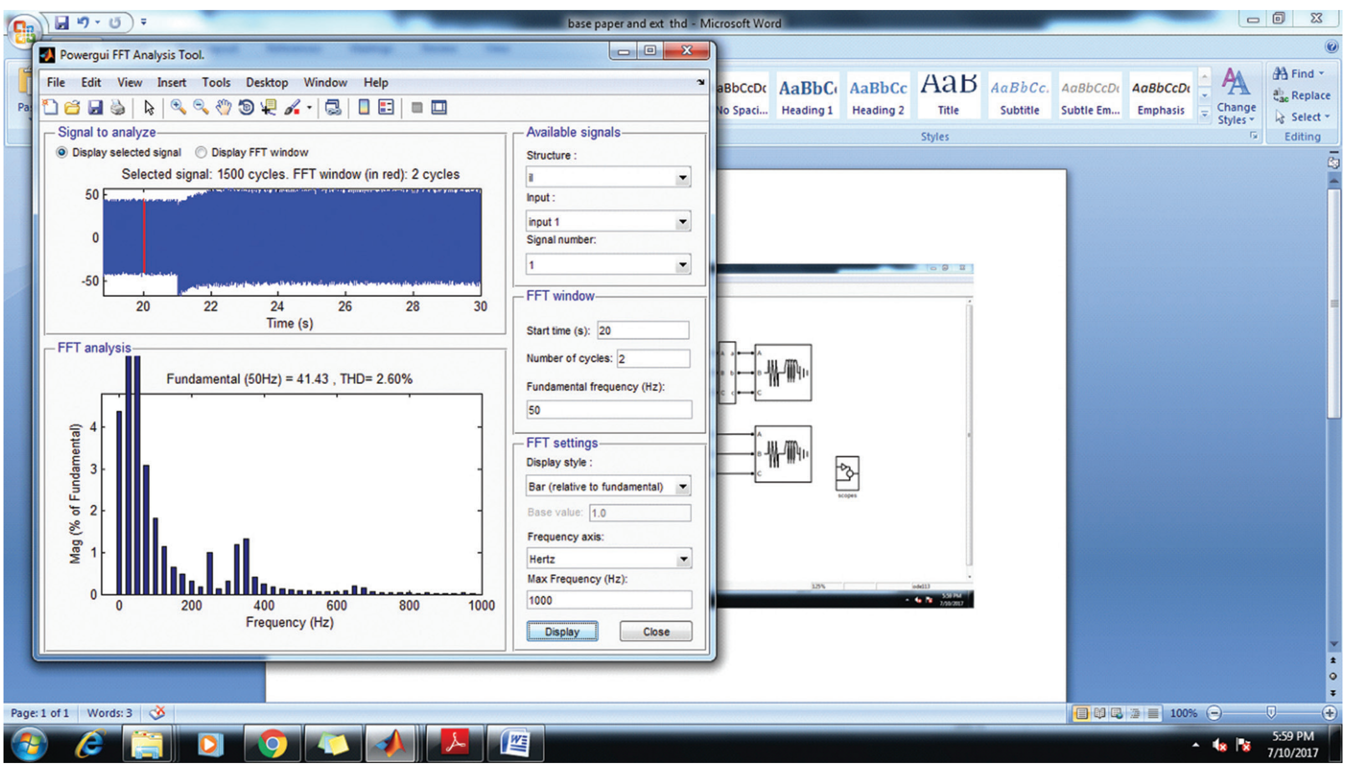
Figure 7(a) and Figure 7(b) are the simulation results of THD values when both DGs are controlled by enhanced VSG control with PI and FLC respectively. From the both results, it is very clear that the total harmonic distortion is reduced when enhanced VSG control is used along with FLC.

6. Conclusion

In this paper, an enhanced VSG control with FLC is proposed as a novel communication-less control technique in a microgrid. A stator reactance adjuster is developed which increase the active power damping and properly shares the transient active power. A novel communication-less reactive power control method based on inversed voltage droop control (V–Q droop control) and common AC bus voltage estimation is also proposed to accomplish exact reactive power sharing, which is immune to active power sharing change and line impedance mismatch. The proposed upgraded VSG control along with fuzzy logic

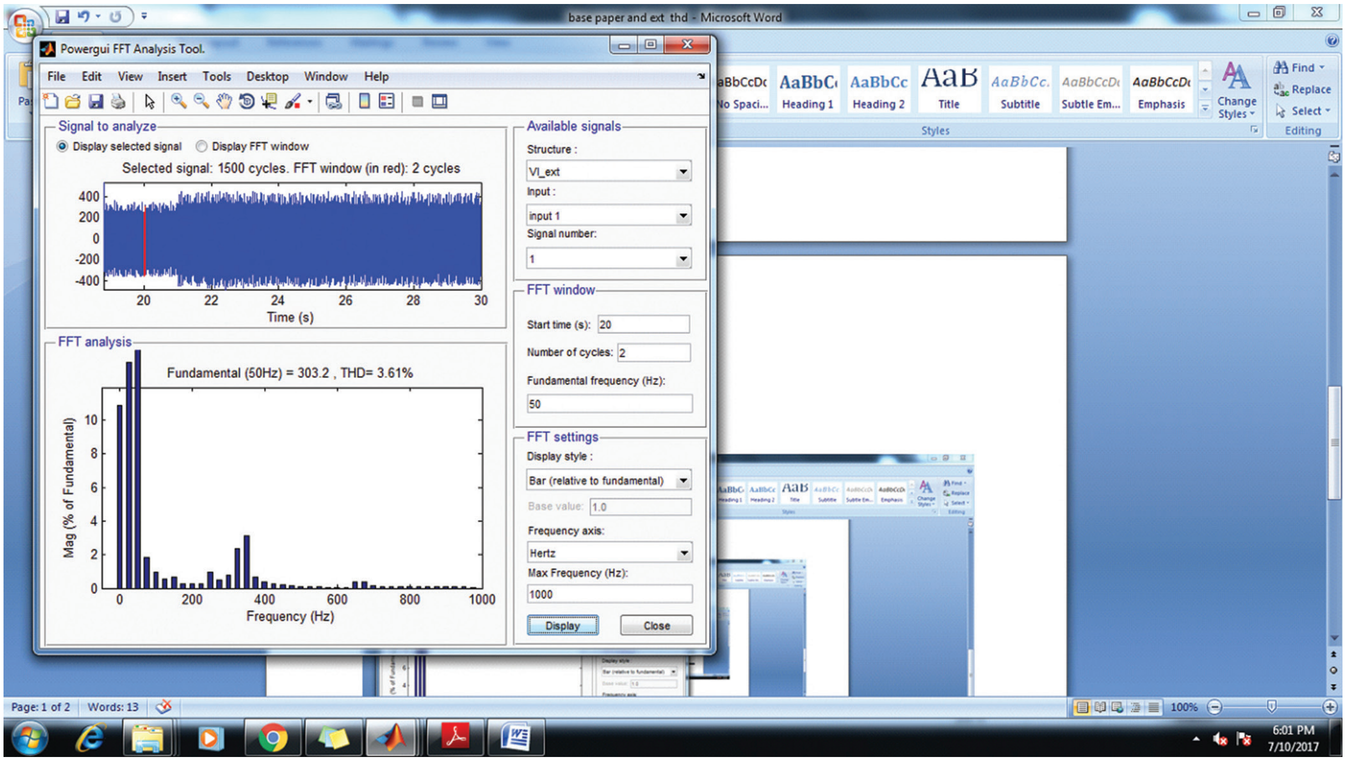


Load voltage THD

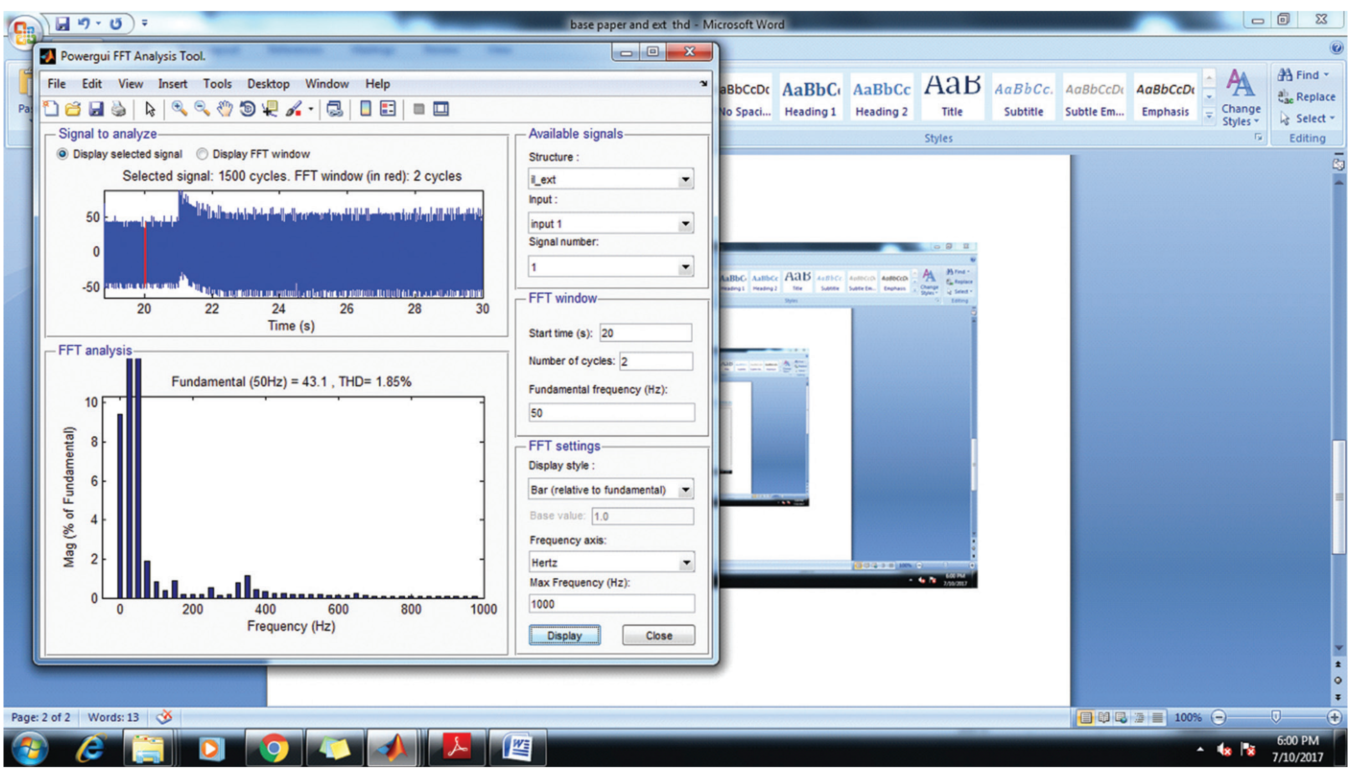


Load Current THD

Figure 7(a). THD values when both DGs are controlled by enhanced VSG control with PI controller.



Load Voltage THD



Load Current THD

Figure 7(b). THD values when both DGs are controlled by enhanced VSG control with FLC.

controller achieves desirable transient and steady-state performances, and keeps the inertia support feature of VSG control. So, the proposed enhanced VSG control with FLC is an ideal decision for controlling the DGs in micro grids.

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